Technologies to Improve Ion Propulsion System Performance, Life and Efficiency for NEP

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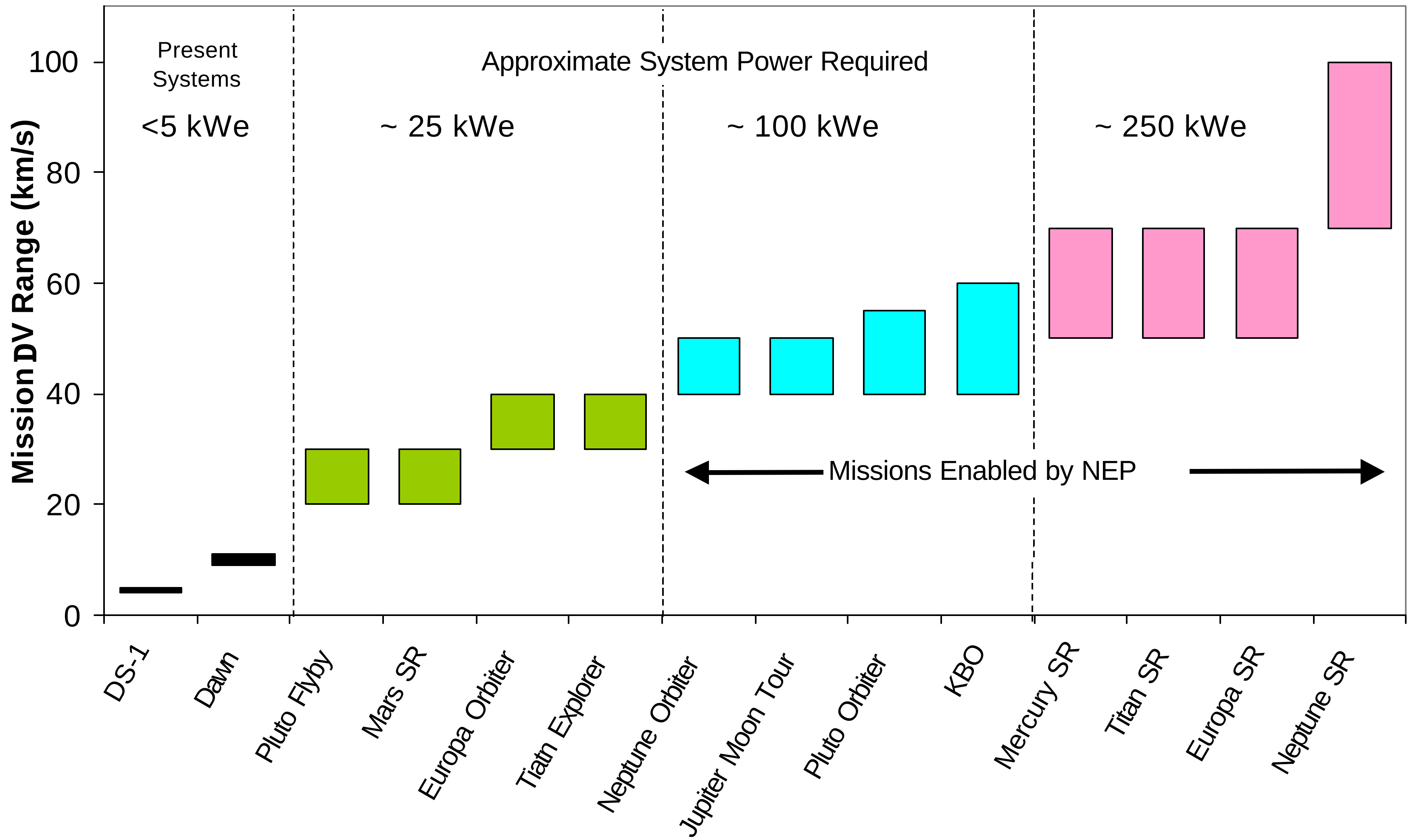
Outline

- **Potential NEP Missions require major advances in electric thrusters**

Specific Impulse (Isp)	3,000 s	→	7,000s
Beam voltage	1,100 V	→	5,000 V
Power	2,500W	→	10,000W
Throughput increase	200 kg	→	1,000 kg
Life	3 yrs	→	10 yrs

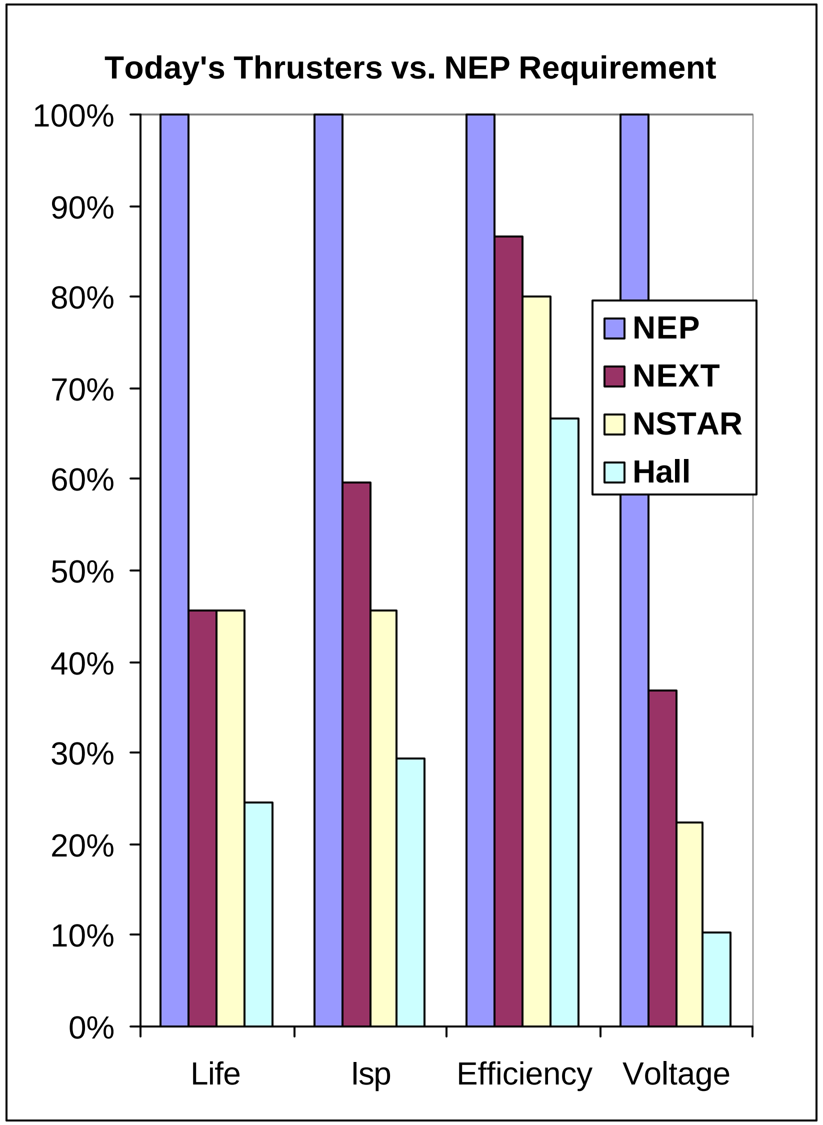
- **Ion Engines Clear Choice For Potential Near Term NEP Missions**
  - Ion Propulsion Background
  - NASA's Solar Electric Propulsion Technology Programs
- **Nuclear Electric Xenon Ion System (NEXIS) Program**
  - JPL Computer Models: Ion Thruster Design Tools
  - Ion optics grid performance & life
  - Hollow cathode life
- **Thruster plume – S/C interactions**
- **Summary**

Mission ΔV's for Potential NEP Missions



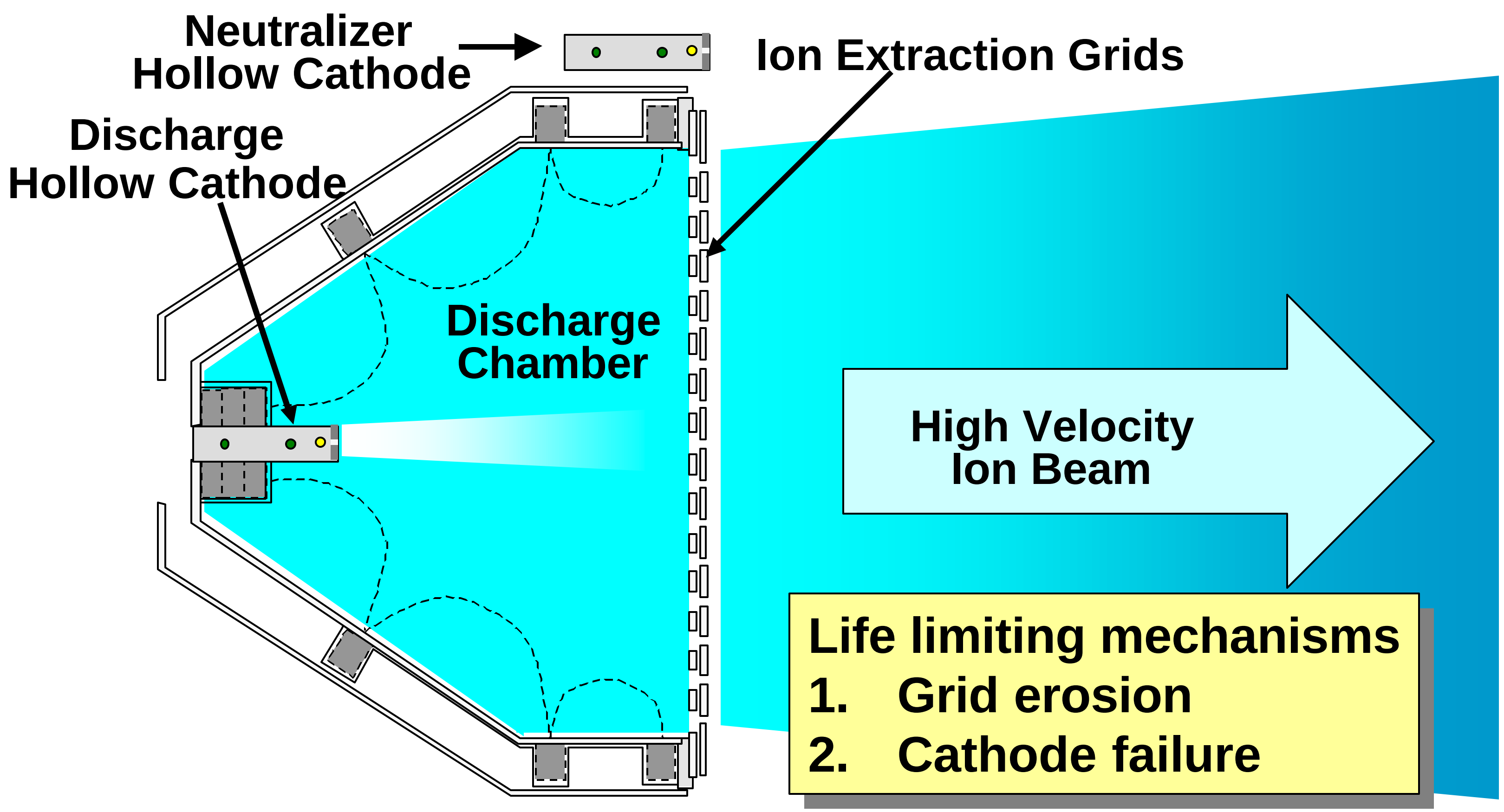
Gridded Ion Thrusters: Clear Choice For Near Term NEP

- **Ion thrusters scale well to high power & Isp**
  - Voltage & power increase with Isp^2
  - e. g. NSTAR 3100 s 2.3kW, 7000 s ~ 10 kW
- **High Isp readily achievable with ion thrusters**
  - Increased grid voltage increases ion exit velocity
  - Demonstrated in the lab >> 12,000 s Isp
- **High efficiency comes naturally at high Isp**
- **Key challenge is achieving thruster life**
  - NSTAR Extended Life Test demonstrated 27,000+ hrs
  - Life validation must use accelerated tests & analysis
- **Grid and Cathodes are the keys to long life**
  - Grid erosion increases ~ linearly with voltage
  - Hollow cathode life models are needed

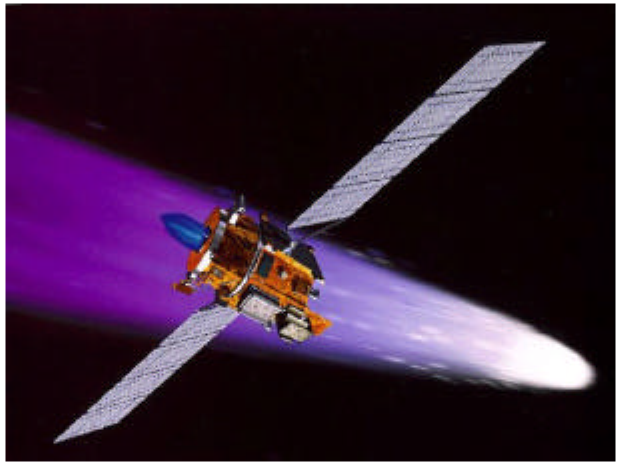


Gridded Ion Thruster Basics

1. Xenon gas **ionized** in the discharge chamber
2. Ion **accelerated** electric field between grids
3. Ion beam charge and current **neutralized** by neutralizer electrons

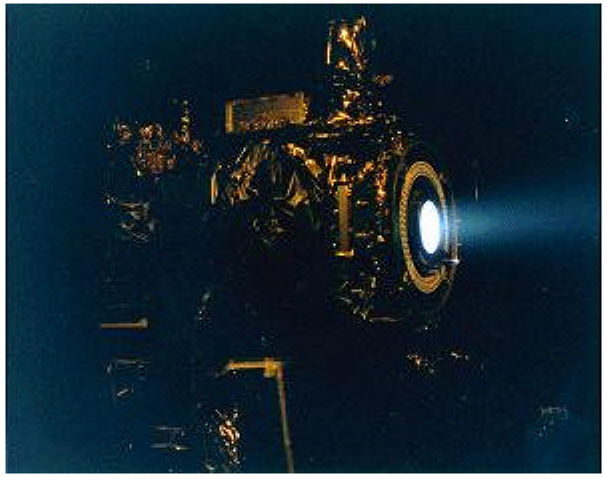


Deep Space 1
Successful Ion Propulsion Mission

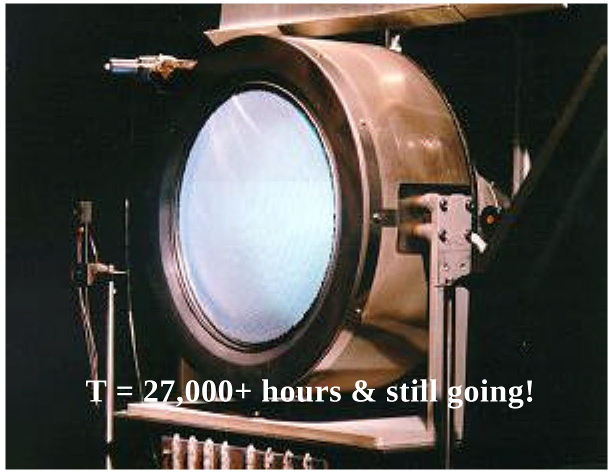


Deep Space 1 flew by the comet Borrelly in 2001, collecting valuable science data.

- **Deep Space 1 Flight Engine Developed by JPL Managed Team**
  - NSTAR Project (JPL, GRC, industry, universities and international partners)
- **Deep Space 1 Ion Engine Life Testing Performed by JPL**
  - 1000 hour validation test
  - 8200 hour Life Demonstration Test
  - Ongoing Extended Life Test (26,000+ hours)
- **Deep Space 1 Flight System Integration and Functional Tests**
  - End-to-end system demonstration in thermal-vacuum test
- **Deep Space 1 NSTAR Flight Diagnostics Package**
- **Deep Space 1 Flight Operations and Successful Mission**
  - 16,265 hours of operation in space
  - Hyper-Extended Mission – NSTAR thruster tests



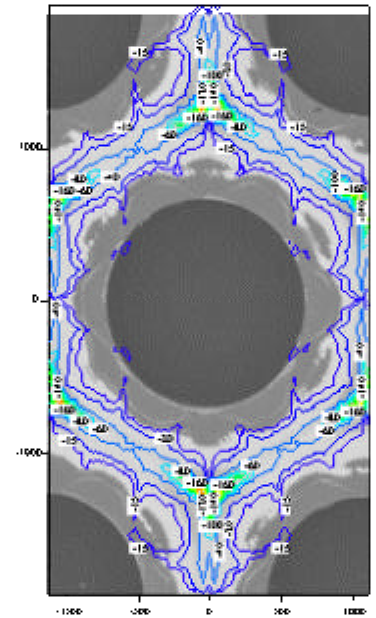
Flight ion engine firing on Deep Space 1 spacecraft during solar thermal vacuum test.



World's longest ion engine endurance test is presently underway at JPL.

NSTAR Extended Life Test
Data for Ion Thruster Service Life Validation

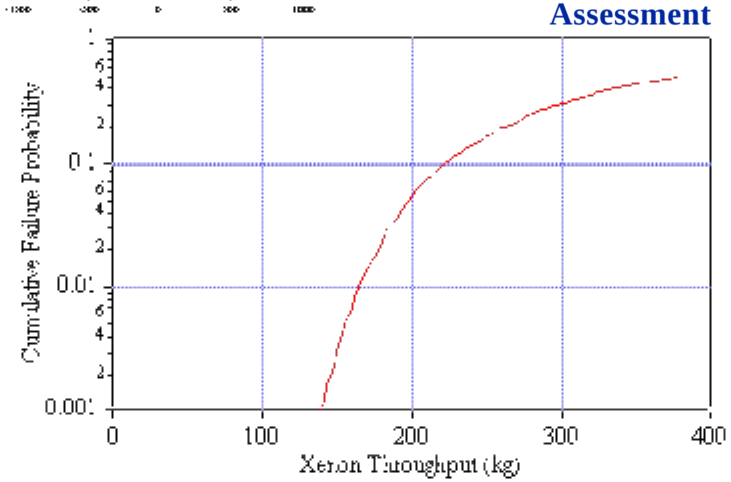
- **Long Duration Tests to Identify and Characterize Failure Modes**
  - 10 kWe test (1988)
  - 5 kWe test (1990)
  - Test-to-Failure Test (1993)
  - NSTAR Testing
    - 2000 Hour Test (1994)
    - 1000 Hour Test (1995)
    - 8200 Hour Test (1998)
    - 27000+ Hour Test (Ongoing)
- **In-Space Data from the Deep Space 1 Spacecraft to Characterize Failure Modes and Validate Ground Measurements**
- **Probabilistic Analysis to Assess Service Life**
  - Relatively simple analytical models of failure process embedded in Monte Carlo simulation
  - Experimental data and additional modeling to characterize parameter distributions
- **Modeling of Plasma and Surface Processes**
  - Particle-in-Cell code simulations of ion acceleration and charge exchange process
  - Hollow cathode physics models
  - Surface kinetics modeling of simultaneous sputtering and deposition



Testing

Modeling and Analysis

Probabilistic Failure Assessment

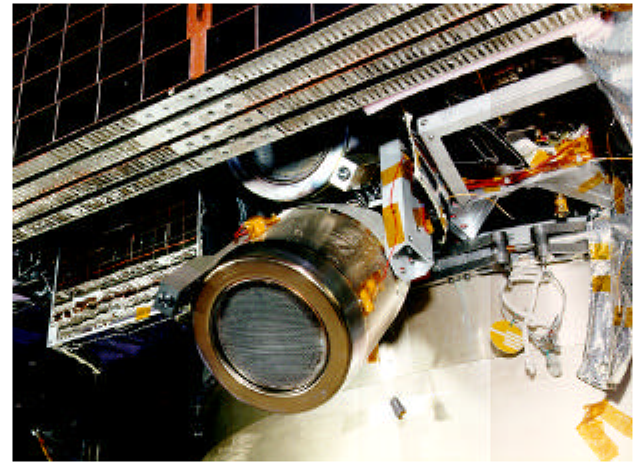


Xenon Ion Propulsion Used Extensively on Commercial GEO Communications Satellites

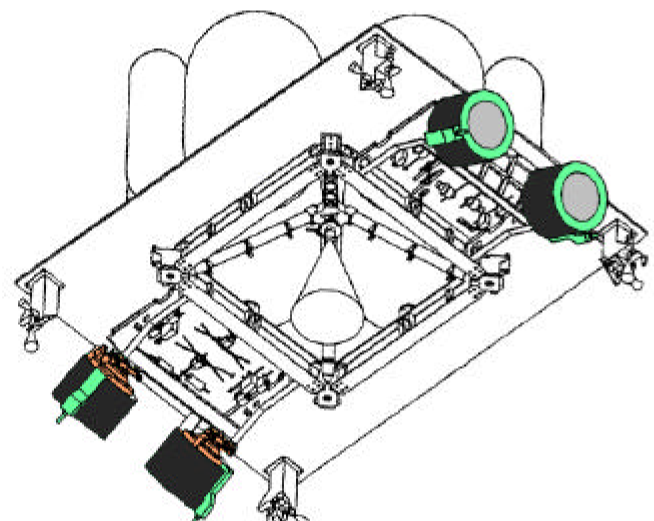
- Boeing has launched 13cm XIPS thrusters since 1997 and 25cm XIPS thrusters since 1999

<u>19 Satellites</u> **<u>76 Thrusters</u>**

- **52** of the 13 cm ion thrusters and 26 PPUs are in-orbit on thirteen 601HP communications satellites
  - **>55,000 hours of operation accumulated to date**
- **24** of the 25-cm ion thrusters and 12 PPUs are in–orbit on six Boeing 702 communications satellites
  - > **4500** hours of high power orbit insertion
  - > **9000** hours of low-power station keeping
- Transmitter tubes operate 5,000-10,000V

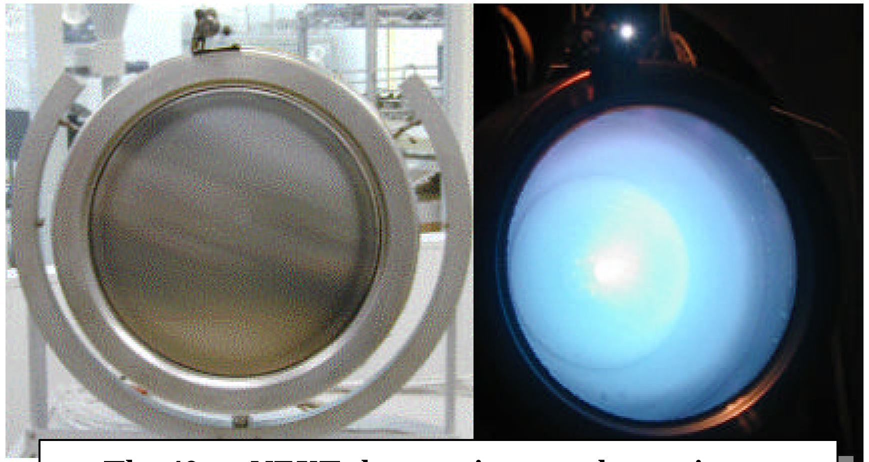


13-cm Xenon Ion Propulsion System on the HS-601 Spacecraft Bus.



Boeing 702 Satellite 25cm XIPS

NASA's In-Space Propulsion NEXT Program: NASA's Evolutionary Xenon Thruster – System



The 40cm NEXT thruster is more than twice as powerful as today's NSTAR thruster.

Description of Technology:

40-cm diameter ion thruster

Throttle Range: 1 kW – 6.25 kW

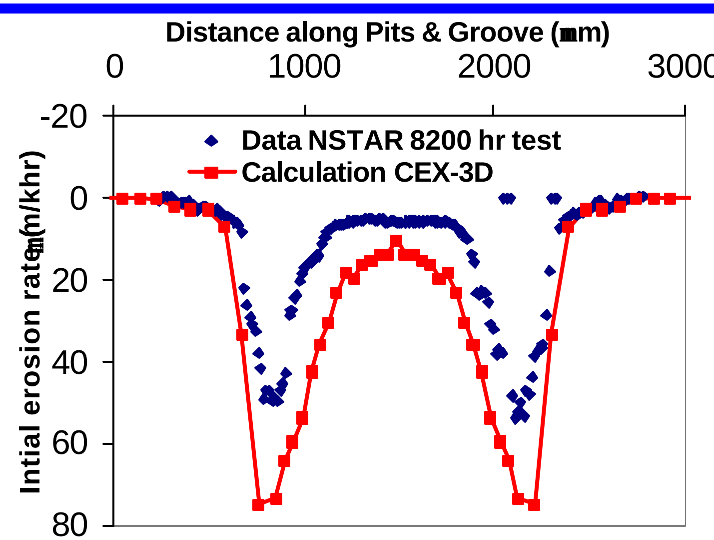
Maximum Isp 4050 seconds

71% engine efficiency.

Status: Laboratory Model thruster manufactured and performance characterized. Engineering Model engine under test. PPU beam supply manufactured and tested.

Developers: NASA Glenn Research Center (Lead), the Jet Propulsion Laboratory, Boeing Electron Dynamic Devices, General Dynamics-Space Propulsion Systems, Applied Physics Laboratory, Colorado State University, University of Michigan

Managed by: NASA/MSFC



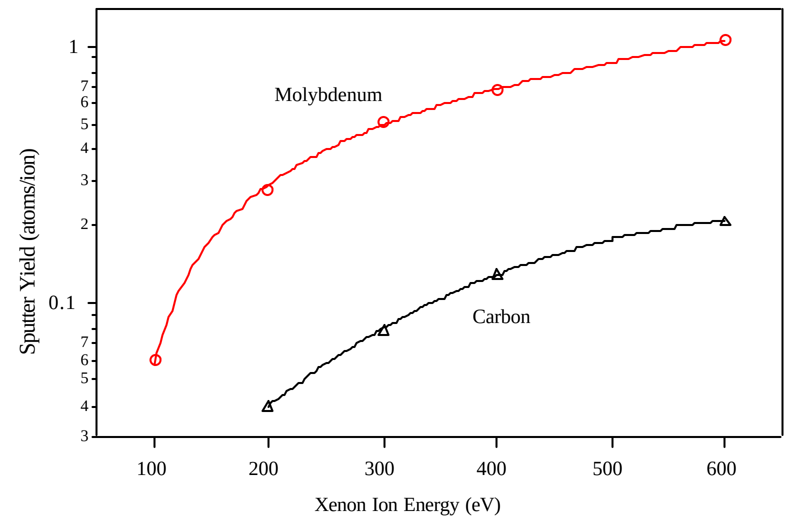
JPL leading the service life validation activity

NASA's In-Space Propulsion CBIO Program
Carbon Based Ion Optics for Long-Life, High-Isp Thrusters

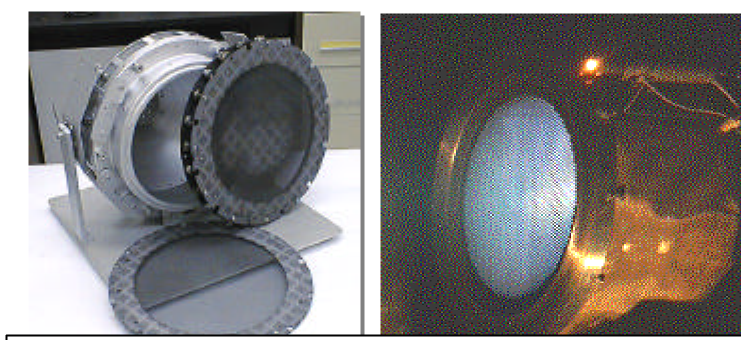
- **Advanced carbon grid materials offer dramatic improvements in ion engine technology**
  - Carbon erosion resistance essentially eliminates grid wear out failure modes
- **Goals and Objectives**
  - Develop 30-cm carbon-carbon grids
  - Validate the performance and life of the carbon-carbon grids
  - Develop and deliver grid life modeling software
- **Key Challenges**
  - Achieving required beam extraction characteristics
  - Demonstrate ability to survive launch loads
  - Demonstrate ability to provide sustained operation with acceptable arcing at the required electric field
- **Accomplishements**
  - **30cm Carbon – Carbon Grids**

    <u>**Running at 5000s *Isp* !**</u>
  - **Analysis shows CC grid will survive launch loads**

<u>Managed by</u>: NASA/MSFC

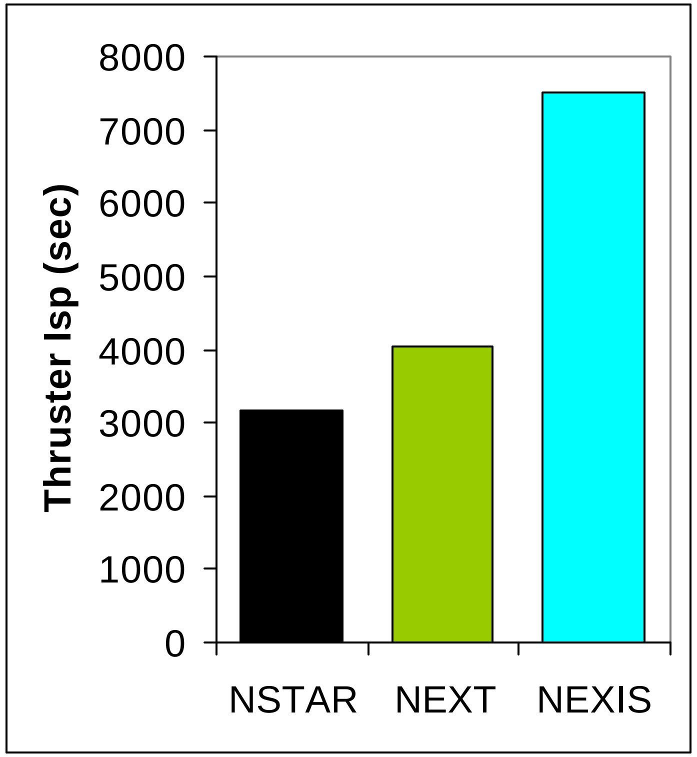


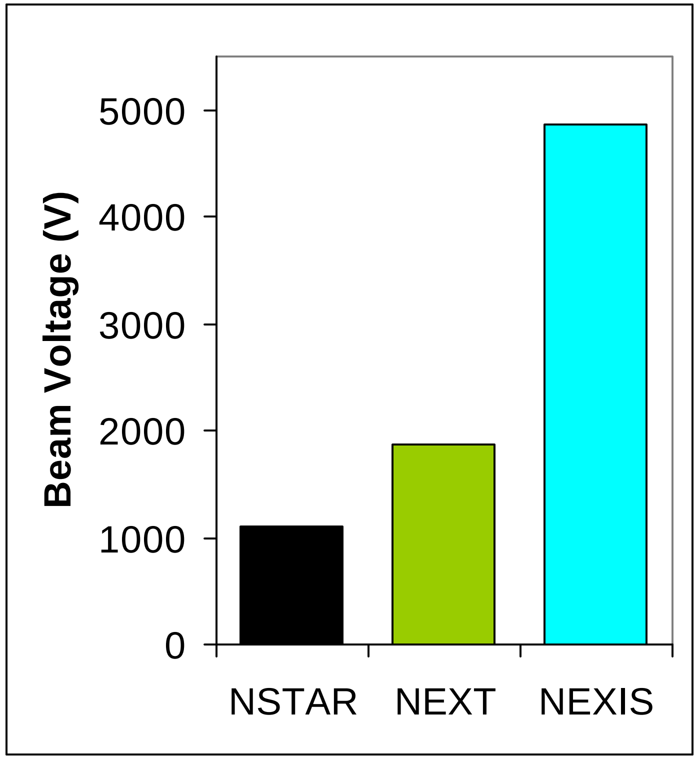
Carbon reduces grid erosion by almost an order of magnitude



30 cm Carbon-Carbon Grids Operating at 5000s *Isp*

Nuclear Electric Xenon Ion System (NEXIS) Program Addresses Requirements of Potential NEP Missions





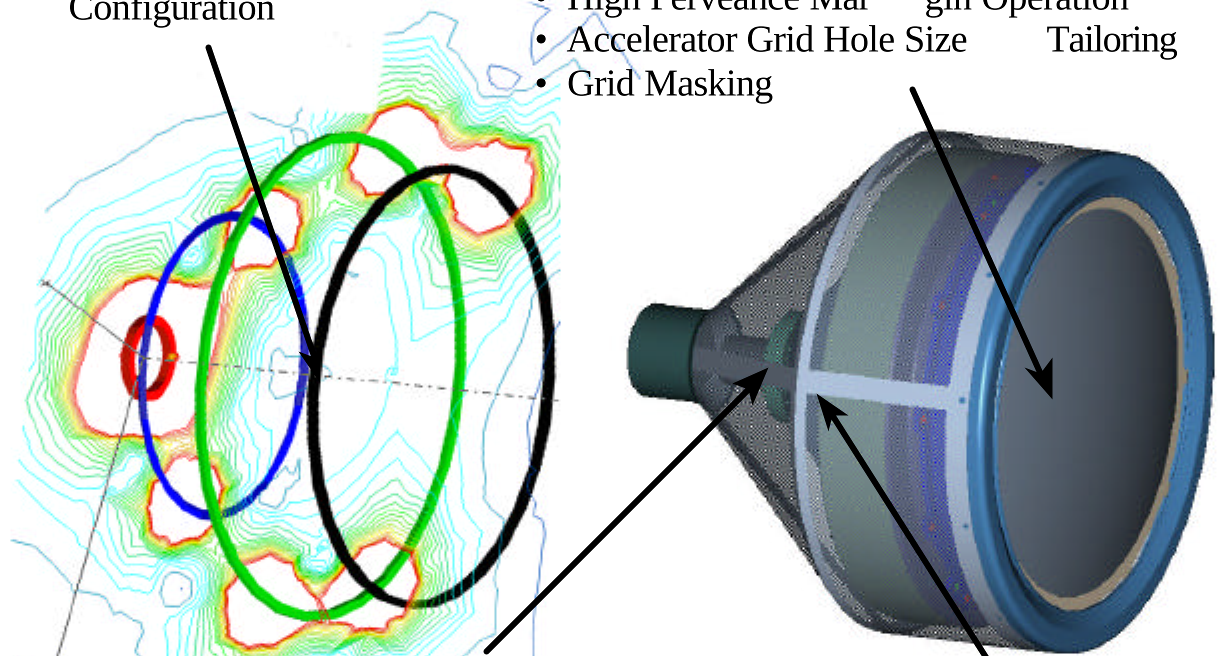
NEXIS a major advance in ion thruster performance

NEXIS Advances Ion Thruster Technology

Performance Metric	NEXIS
Power (kWe)	20
Isp (s)	7500
Thruster Efficiency	0.78
Specific Mass (kg/kWe)	1
Throughput (kg)	1000
Run Time (hrs)	48,000

- Large Discharge Chamber
- Advanced Ring Cusp Magnetic Field Configuration

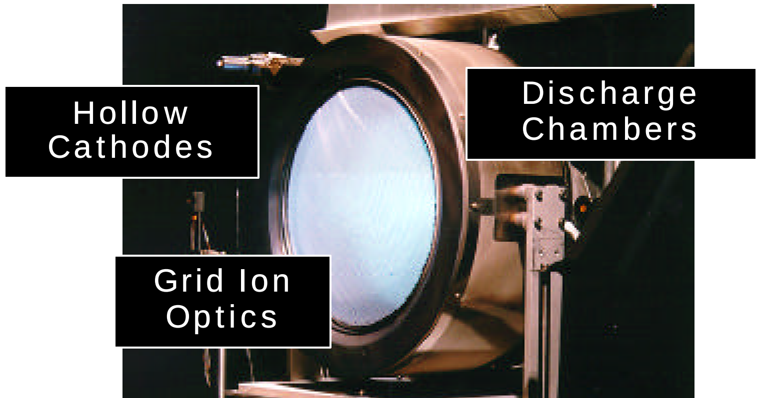
- Beam Voltage > 4860 V
- New Grid Design Using Advanced Simulation Tools
- Erosion-resistant Carbon Carbon Grids
- High Perveance Margin Operation
- Accelerator Grid Hole Size Tailoring
- Grid Masking



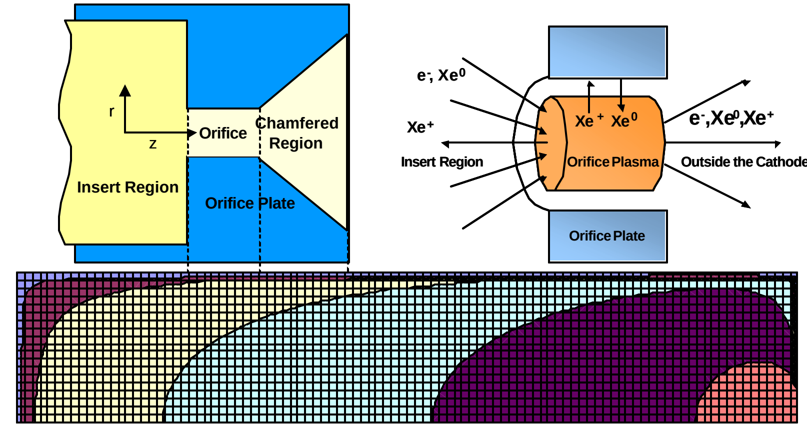
- Reservoir Hollow Cathode Incorporating:
  - -Advanced Emitter Material
  - -High Capacity Activator Supply Reservoir
  - -Improved Activator Transport
  - -Decoupled Emitter and Activator Source
- One Neutralizer Shared By Multiple Engines

- Erosion-resistant Carbon Keeper Electrode
- Operational Control of High Energy Ion Production

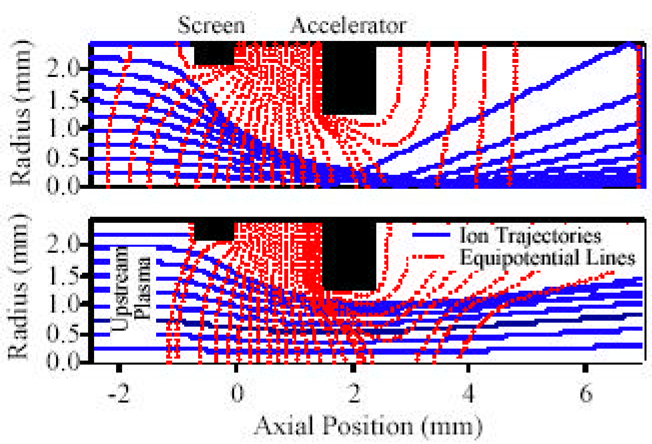
JPL Computer Models: Ion Thruster Design Tools



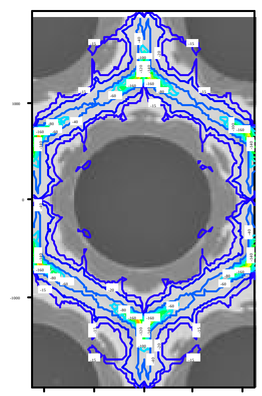
Computer models are used to guide design, correlate test data & predict engine life
Validated with lab & flight performance & wear data



Hollow cathode orifice and discharge chamber models include ionization physics

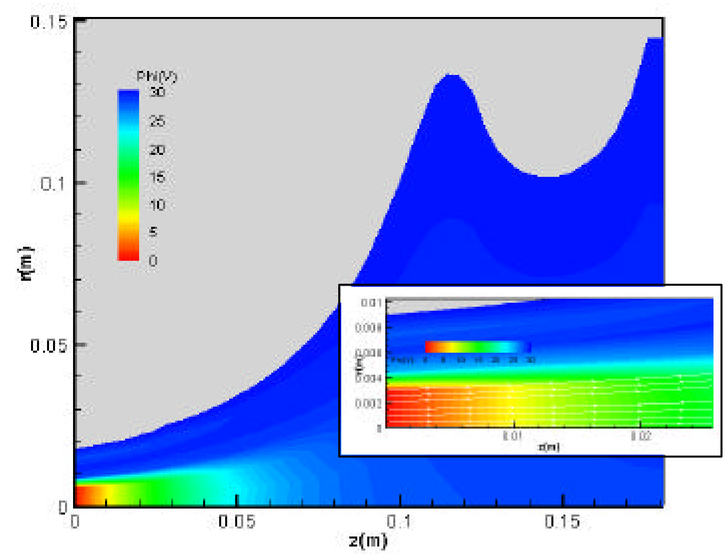


ion trajectories



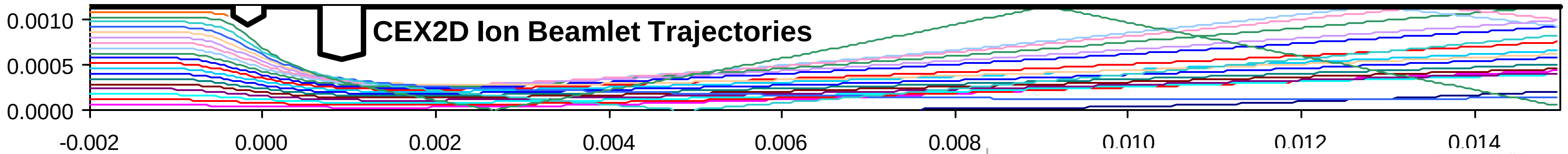
erosion pattern

Codes model ion trajectories and erosion of a single grid aperture



Discharge chamber potentials

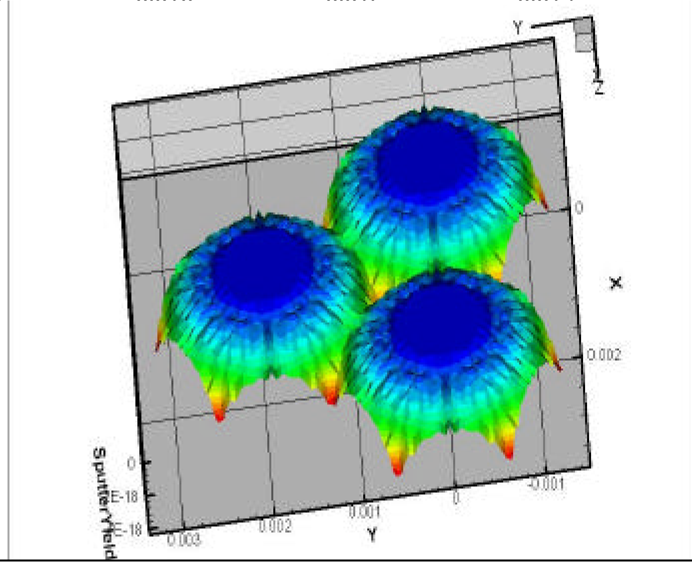
JPL Grid Ion Optics Codes



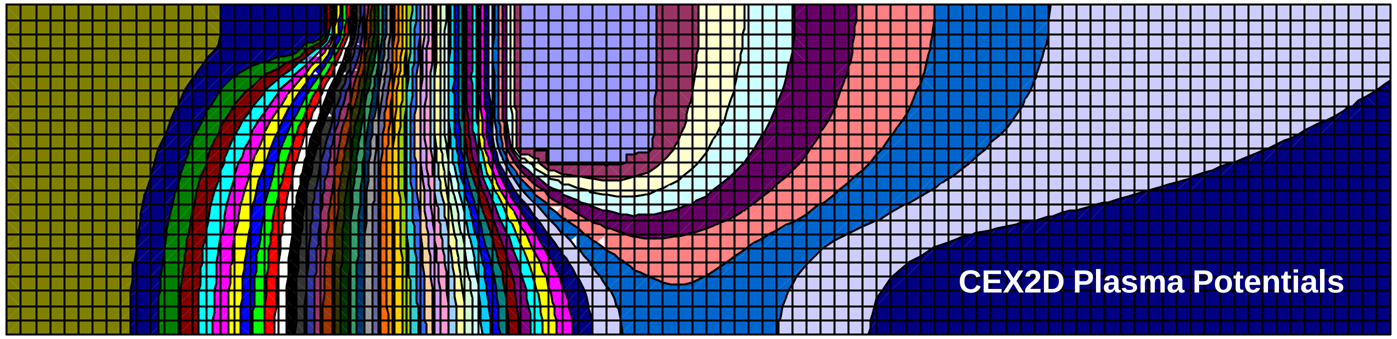
CEX2D : 2-D R-Z including charge exchange ions (that cause erosion)

CEX3D : 3-D right triangular prisms (minimum symmetry region)

- Physics
  - Potentials: Poisson's equation
  - Ion density: tracked trajectories using calculated electric fields
  - Electron density: analytic – assumes Maxwellian's upstream & downstream
  - Charge Exchange (CEX) collisions
- Advanced Numerical Techniques



CEX3D calculated "Pits and Grooves" erosion pattern



Ion Optics Codes Validated with NSTAR Data

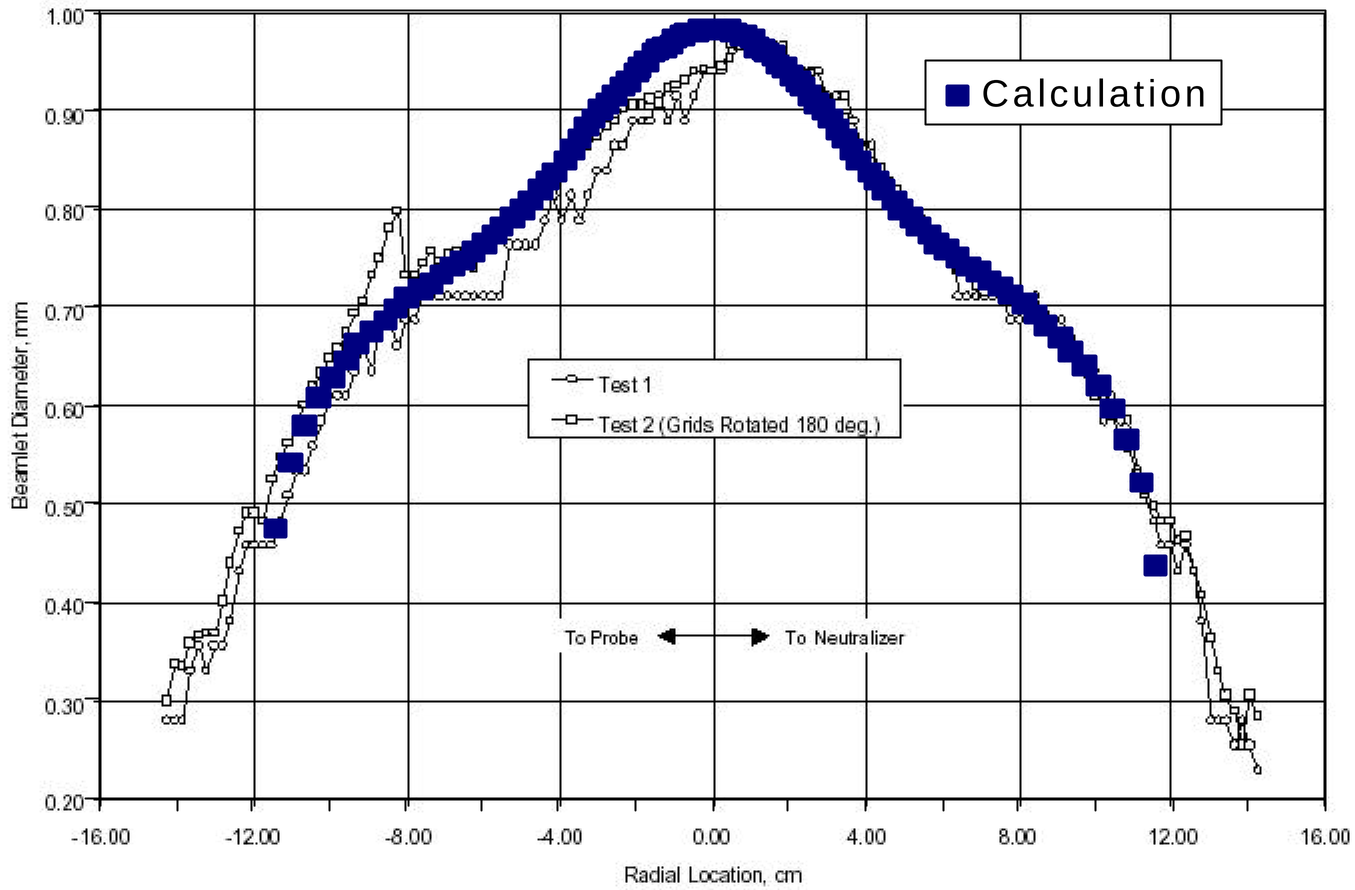
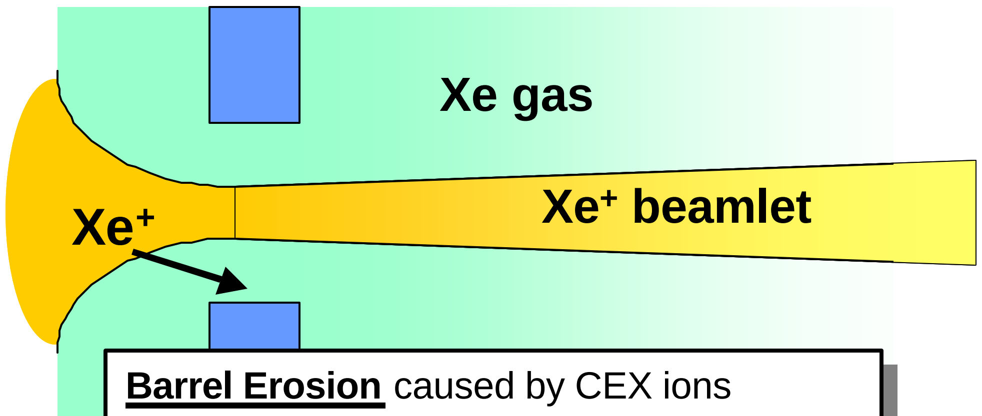


Fig. 7 Beamlet exit diameters as a function of radius for tests 1 and 2.

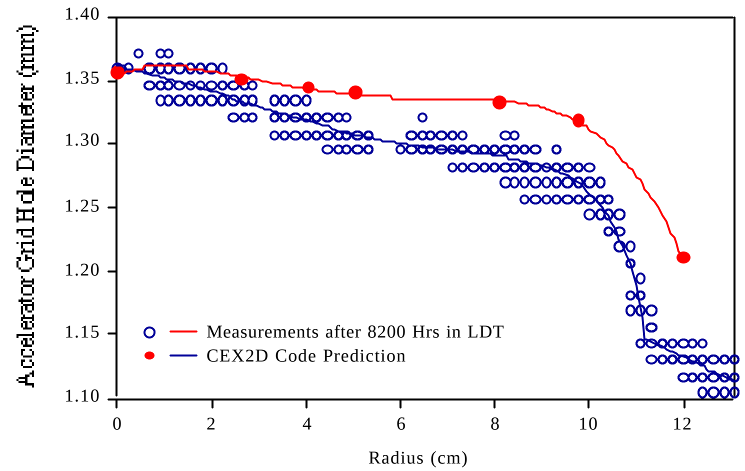
George Soulas and Vince Rawlin, Beamlet Diameter Measurements, 3/22/99

Grid Erosion

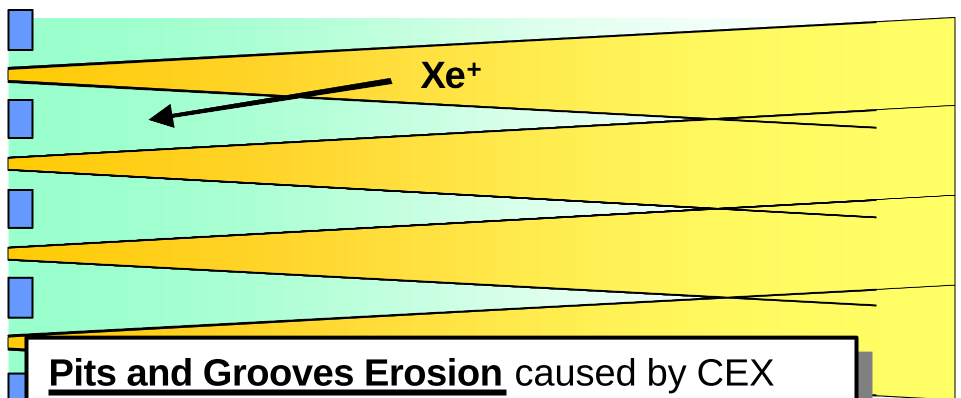
- Charge Exchange (CEX) collisions between beam ions and neutral gas produce slow ions that can impact grid surfaces



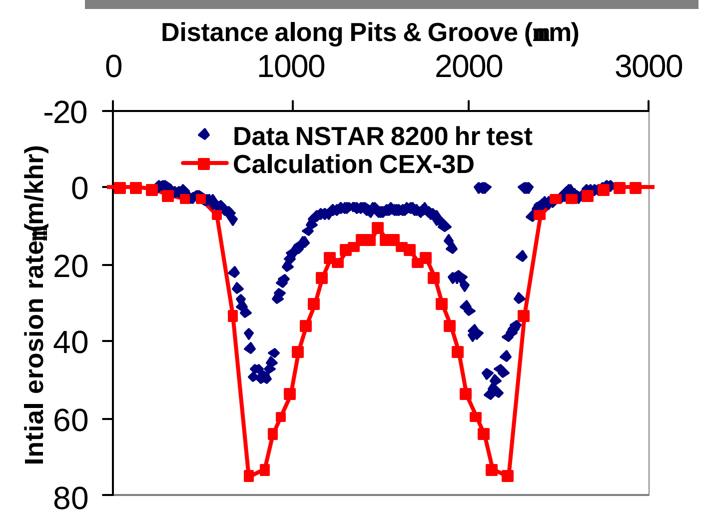
Barrel Erosion caused by CEX ions generated upstream and in accel grid hole



Comparisons with NSTAR Data

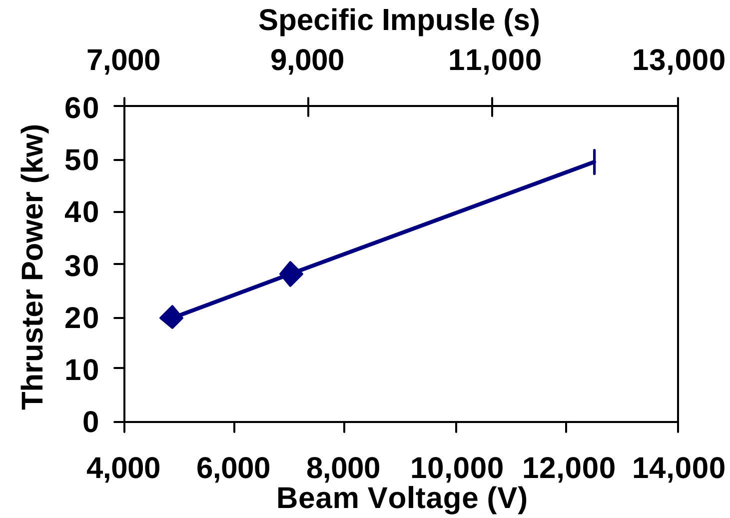


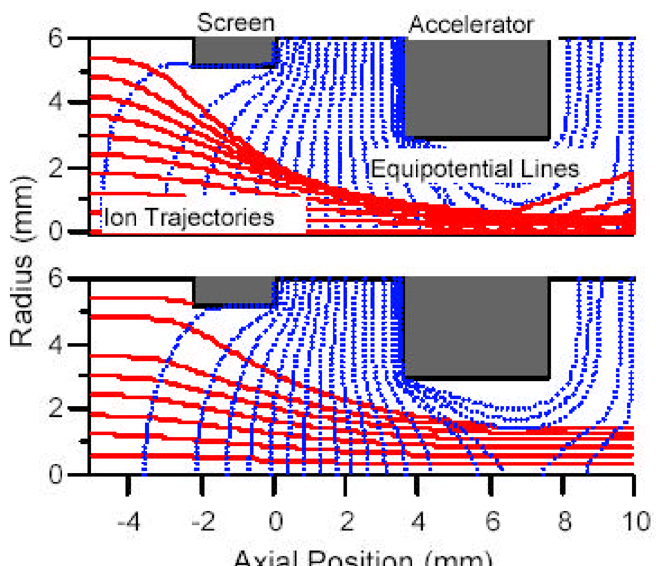
Pits and Grooves Erosion caused by CEX ions generated downstream



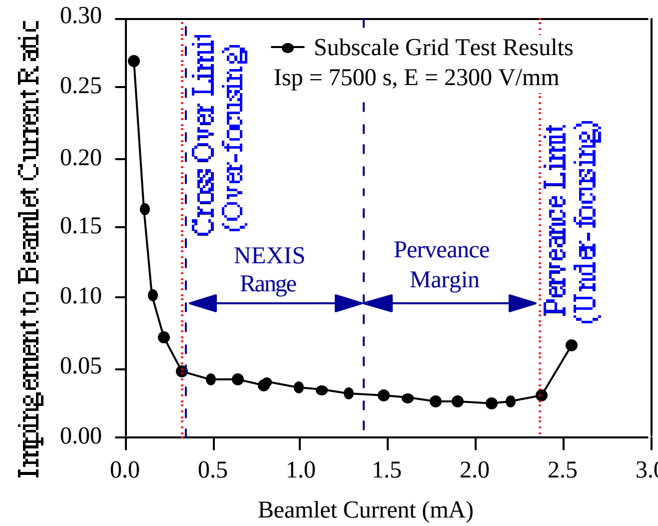
NEXIS Isp = 7500s Grid Design

- High ISP means high grid voltage
  - Thruster power increases rapidly
  - Discharge chamber doesn't change
- High Isp grids designed using computer codes
- Laboratory test validate designs





The NEXIS grid design provides proper beamlet focusing at low densities (top) and high densities (bottom)



Beam extraction tests with subscale grids show desired beam extraction characteristics.

Hollow Cathode Fundamentals

- Efficient source of electrons
- Partially ionizes a neutral gas
  - Input: propellant gas, e. g. Xenon
  - Output: electrons, ions, and unionized gas
- Electron current >> ions emitted
  - Electrons emitted from low work function Barium impregnated insert
- Failure modes
  - Insert Ba depletion
  - Orifice erosion or blockage
  - Keeper erosion

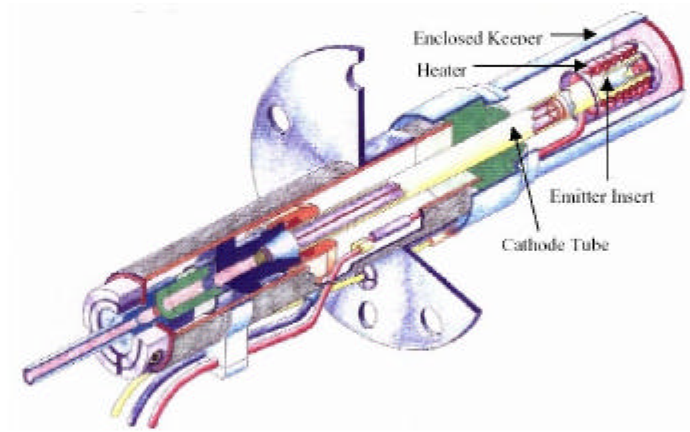
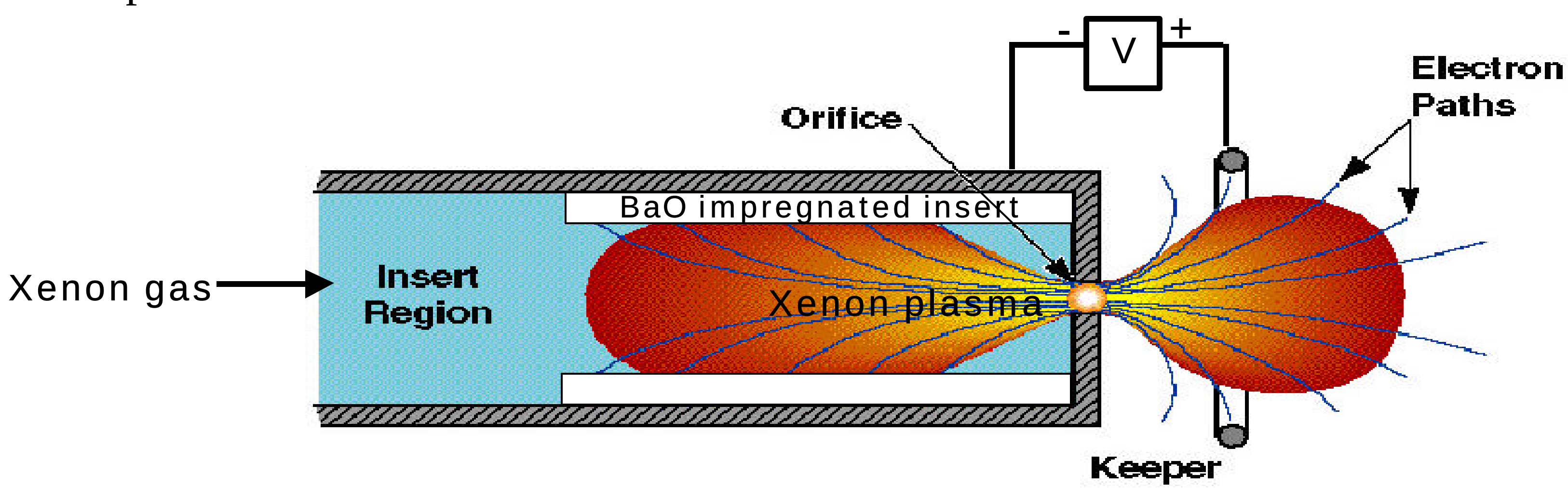


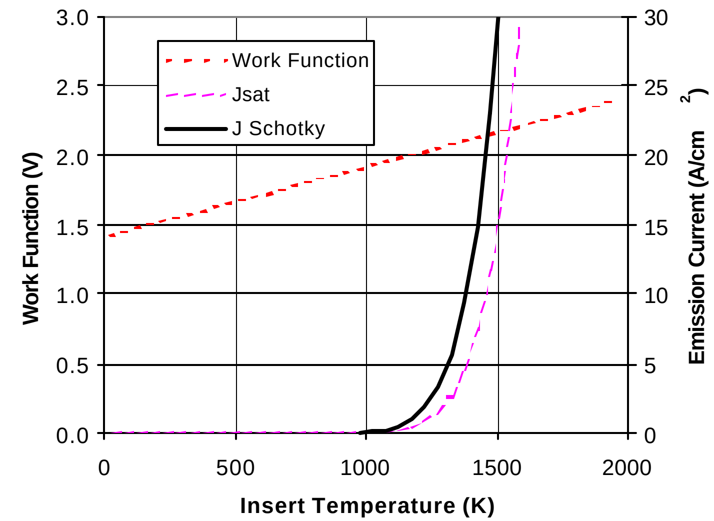
Figure 1. Drawing of a flight HCA (drawing not to scale).

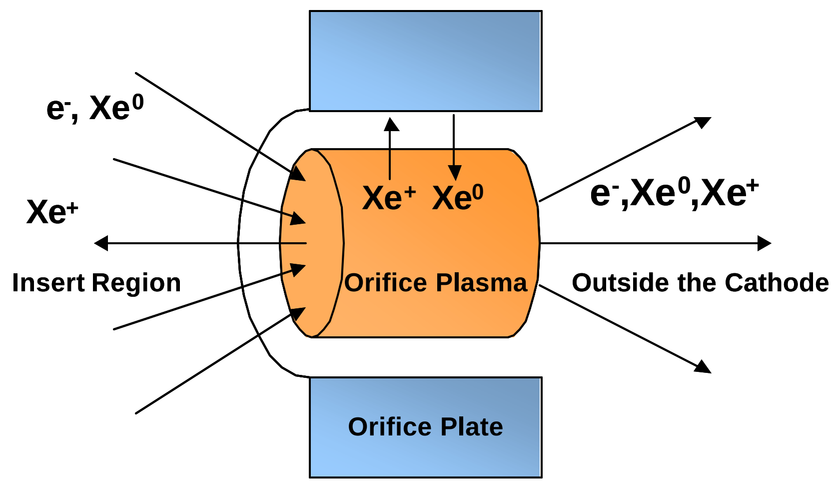
Figure from "A Review of Testing of Hollow Cathodes for The International Space Station Plasma Contactor" S. D. Kovaleski, M. J. Patterson, G. C. Soulas, T. R. Sarver-Verhey, NASA Glenn Research Center, IEPC-01-271



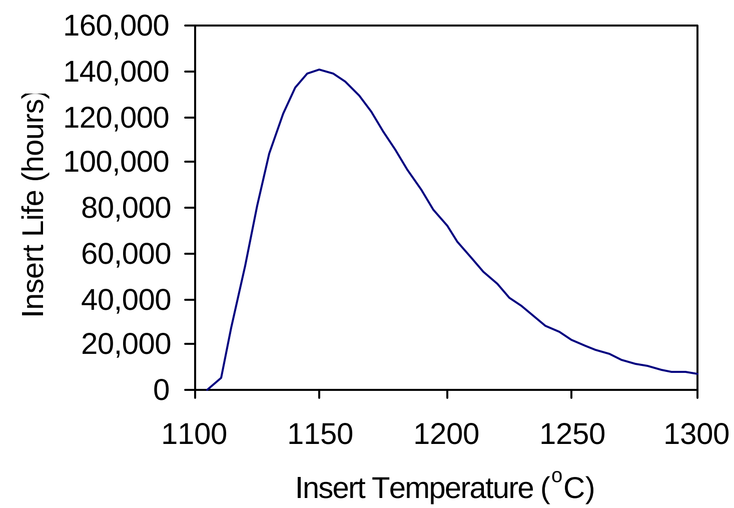
Increasing Hollow Cathode Insert Life

- Potential NEP Missions require 10 yr cathode life
  - Space Station Plasma Contactor life test
    - demonstrated 28,000 hrs life,very hard to start ~ 24,000 hrs
  - NSTAR Extended Life Test Discharge Cathode
    - presently at 27,400+ hrs, shows no sign of degradation
- Hollow Cathode models provide physical insight
  - Barium is ionized and migrates upstream
  - Orifice dimensions and current control insert temperature
- Methods to increase insert life
  1. More barium ➔ Dispenser Cathode
  2. Lower work function ➔ Tungsten – Iridium
  3. Lower operating temperature ➔ Orifice design





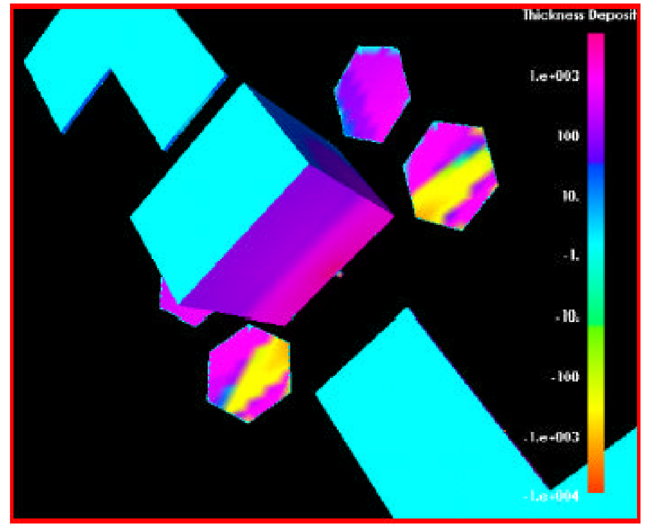
JPL Models of Hollow Cathode Physics



40° C Reduction Doubles Insert Life

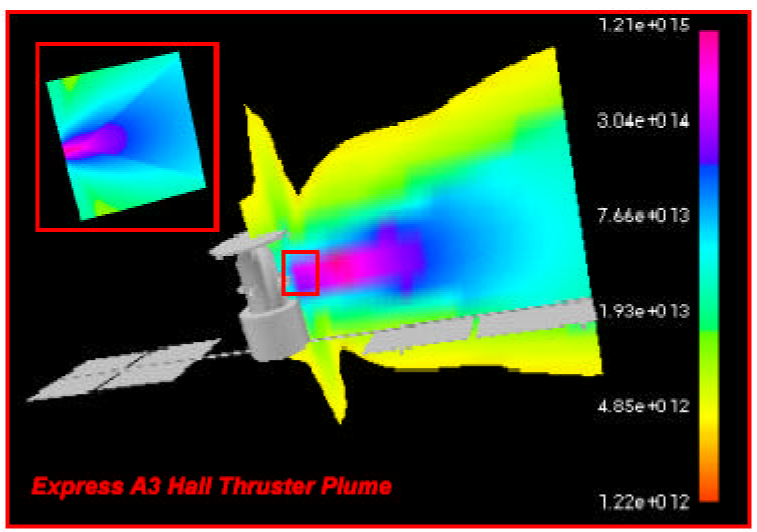
Computer Models Will Be Used to Address EP Thruster Plume - S/C Integration Issues

- Ion thruster plume components
  - Energetic beam ions
  - Charge exchange plasma
  - Scattered ions
  - Grid erosion products
- Plume-Spacecraft interactions
  - Sputter erosion of surfaces
  - Contamination of radiators, optics, & antennas
  - Plasma optical & RF emissions
  - Plasma dielectric effects
  - Mechanical & thermal loads

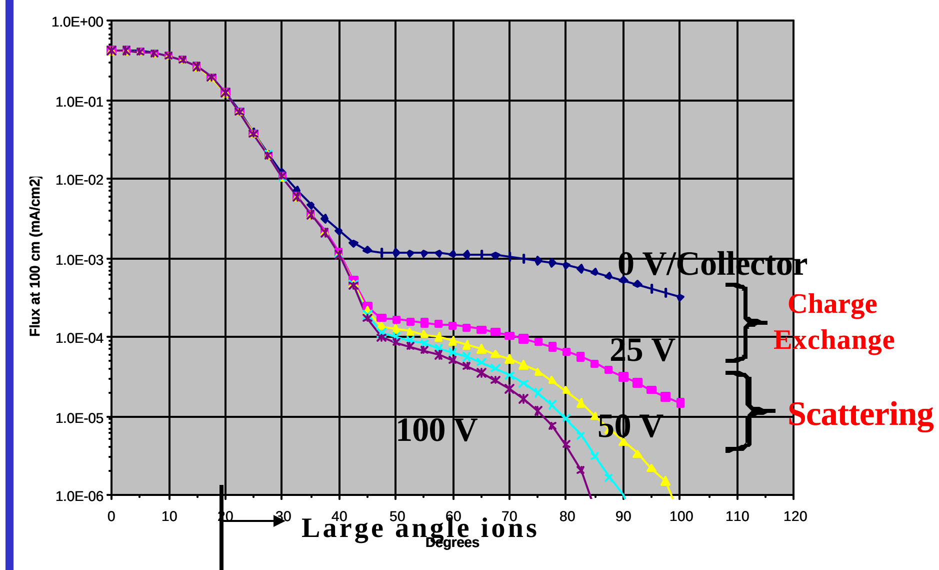


Calculated material sputtering and redeposition

Plume model integrated with spacecraft geometry



Thruster plumes have high energy particles at large angles



Summary

- Gridded Ion Engines Clear Choice For Potential Near Term NEP Missions
- Potential NEP Missions require major advances in ion thrusters
- Extensive Ion Thruster Heritage
    - Knowledge
    - Flight
    - Laboratory Life Test
- In-Space technology programs don't address potential NEP Mission requirements
    - NEXT - NASA's Evolutionary Xenon Thruster
        - Bigger discharge chamber, Modest Isp increase (4000s)
    - CBIO - Carbon Based Ion Optics
        - Low sputter yield material for long grid life, demonstrated at 5000s Isp
- Nuclear Electric Xenon Ion System (NEXIS) Program
    - Advanced Technologies that Enable NEP
        - High efficiency discharge chamber
        - High Isp, long life, carbon based grids
        - Dispenser hollow cathodes for long life
    - Designed using JPL Ion Thruster Codes
        - Ion optics grid performance & life
        - Hollow performance & cathode life